



**US Army Corps
of Engineers**

Construction Engineering
Research Laboratory

USACERL Technical Report N-90/05

June 1990

FEAP: Pipe Loop System

AD-A225 865

Drinking Water Treatment Optimization Using the Pipe-Loop System: Demonstration at Aberdeen Proving Ground, MD

by
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Army installations must comply with the various Federal and state regulations on potable water quality, which are becoming increasingly stringent. A problem facing installations is that while a water may leave the treatment plant at an acceptable quality, it may deteriorate before reaching the consumer. This degradation in quality is mainly due to the introduction of metals (e.g., lead and copper) and other by-products of corrosion occurring along the distribution system.

The U.S. Army Construction Engineering Research Laboratory (USACERL) has developed a low-cost apparatus called the CERL Pipe-Loop System (CERL-PLS) for evaluating corrosion and techniques for its control in drinking water systems. Installations can use this system to optimize their water treatment practices and meet the mandated drinking water standards.

To maximize the CERL-PLS' performance, a standard protocol is needed for simulating water conditions during testing and monitoring. Moreover, in light of proposed new regulations that would lower the acceptable levels of copper and lead, the system required testing to determine if it could help installations develop successful treatment programs. A field test was conducted at the Aberdeen Proving Ground, MD, water treatment plant and experimental data were compared with water system survey data that had been measured previously. The results suggest that the method used to estimate water conditions for the simulation is adequate, but could be refined for better accuracy. However, the CERL-PLS was still able to point toward treatment options that could lower lead and copper concentrations to the proposed levels. This field test was performed under the FY88 Facilities Engineering Applications Program (FEAP).

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
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1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE June 1990	3. REPORT TYPE AND DATES COVERED Final		
4. TITLE AND SUBTITLE Drinking Water Treatment Optimization Using the Pipe-Loop System: Demonstration at Aberdeen Proving Ground, MD		5. FUNDING NUMBERS PE 4A162720 PR A896 WU BO-048		
6. AUTHOR(S) Prakash M. Temkar, Richard J. Scholze, and Edgar D. Smith				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Construction Engineering Research Laboratory (USACERL) 2902 Newmark Drive, PO Box 4005 Champaign, IL 61824-4005		8. PERFORMING ORGANIZATION REPORT NUMBER TR N-90/05		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) HQUSACE 20 Massachusetts Avenue, NW. Washington, DC 20314-1000		10. SPONSORING/MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) USACERL has developed a low-cost apparatus called the CERL Pipe-Loop System (CERL-PLS) for evaluating corrosion and techniques for its control in drinking water systems. Installations can use this system to optimize their water treatment practices and meet the mandated drinking water standards. To maximize the CERL-PLS' performance, a standard protocol is needed for simulating water conditions during testing and monitoring. Moreover, in light of proposed new regulations that would lower the acceptable levels of copper and lead, the system required testing to determine if it could help installations develop successful treatment programs. A field test was conducted at the Aberdeen Proving Ground, MD water treatment plant and experimental data were compared with water system survey data that had been measured previously. The results suggest that the method used to estimate water conditions for the simulation is adequate, but could be refined for better accuracy. However, the CERL-PLS was still able to point toward treatment options that could lower lead and copper concentrations to the proposed levels. This field test was performed under the FY88 Facilities Engineering Applications Program (FEAP).				
14. SUBJECT TERMS Aberdeen Proving Ground, MD corrosion CERL Pipe-Loop System drinking water CERL-PLS			15. NUMBER OF PAGES 42	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR	

FOREWORD

Research and development for the CERL Pipe Loop System was performed for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162720A896, "Base Facility Environmental Quality"; Work Unit BO-048, "Upgrading Army Water and Wastewater Treatment Plants." The field test described in this report was performed as part of the FY88 Facilities Engineering Applications Program (FEAP). The HQUSACE Technical Monitor was F. Eubank, CEMP-EB.

The study was conducted by the U.S. Army Construction Engineering Research Laboratory (USACERL) Environmental Division (EN). Dr. R.K. Jain is Chief, EN.

The following personnel from the U.S. Army Environmental Hygiene Agency were instrumental in collecting lead survey data and providing experimental setups at Aberdeen Proving Ground: Jerry Valcik, Thomas Runyon, and MAJ Kotu K. Phull.

LTC E.J. Grabert, Jr. is Commander of USACERL and Dr. L.R. Shaffer is Director.

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DRINKING WATER TREATMENT OPTIMIZATION USING THE PIPE-LOOP SYSTEM: DEMONSTRATION AT ABERDEEN PROVING GROUND, MD

1 INTRODUCTION

Background

Army installations must comply with the increasingly stringent drinking water quality standards enacted at the Federal level and enforced by state regulations. In addition to the National Primary Drinking Water Regulations, the U.S. Environmental Protection Agency (USEPA) has set National Secondary Drinking Water Regulations to control color, odor, appearance, and other characteristics affecting consumer acceptance of water.

Although the water leaving a treatment plant may meet water quality standards, substantial changes can occur as it passes through the water distribution system before reaching the consumer. Internal corrosion of distribution system piping, plumbing, and fixtures is the primary cause of water quality deterioration. Two toxic metals that can be introduced into drinking water as a result of corrosion are lead and cadmium. Other metals often present due to corrosion can cause perceptible deterioration in water quality; these contaminants include copper (blue stain, metallic taste), iron ("red" water, turbidity), and zinc (metallic taste). The presence of these metals can affect public health as well as acceptance of the water supply and may encourage consumers to use another, potentially less safe, source.

USEPA recently issued a proposed rule¹ for limiting lead and copper in drinking water. This rule notes that most lead enters drinking water via corrosion of plumbing materials containing lead. Further, in the proposed rule, water suppliers unable to meet the recommended lead and copper limitations will be required to optimize their water treatment process to reduce lead and copper dissolution from plumbing system materials. USEPA recommends use of a technique such as a pipe-loop system to simulate conditions in household plumbing and evaluate various treatment options for reducing lead and copper dissolution. [Directorate of Engineering and Housing (DEH) personnel should check with USACERL for exact requirements of the rule and its effective date.]

The U.S. Army Construction Engineering Research Laboratory (USACERL) has developed an apparatus called the CERL Pipe-Loop System (CERL-PLS) to evaluate corrosion and methods for its control drinking water systems. The CERL-PLS is designed to be flexible and to approximate various distribution system conditions. Research and development (R&D) of the system have been described in detail in an earlier technical report².

The CERL PLS can be used successfully in its current state to help installations define their water quality and appropriate treatments. However, because the simulation conditions are critical to a realistic analysis, it would be beneficial to learn more about predicting and emulating those conditions. In addition, assuming that the USEPA-proposed limits on lead and copper may be enacted, it is important to know if the CERL-PLS will provide data useful in optimizing the treatment practices. To help answer these questions, the system was field-tested at the Edgewood Water Treatment Plant, which supplies Aberdeen Proving Ground, MD.

¹Federal Register, Vol 50, No. 160 (August 18, 1988), p 31516.

²T. Prakash, et al., *Development of the Pipe Loop System for Determining Effectiveness of Corrosion Control Chemicals in Potable Water Systems*, Technical Report N-88/12/ADA200105 (U.S. Army Construction Engineering Research Laboratory, August 1988).

Objective

The twofold objective of this research was to:

1. Test the protocol for simulating water conditions inside the CERL-PLS by comparing experimental results with data collected in a previous survey.
2. Assess the CERL-PLS' ability to help managers choose a treatment strategy effective in lowering lead and copper concentrations to the levels proposed by USEPA.

Approach

After complaints about the quality of water reaching consumers at Aberdeen Proving Ground, the U.S. Army Environmental Hygiene Agency (USAEHA) surveyed the water distribution system and compiled data on the various constituents found as well as several operating parameters. These data were useful to USACERL's study because they allowed comparisons between measured values and experimental results obtained using the CERL-PLS.

Two experiments were done on the Edgewood water system: one CERL-PLS was installed to observe the effects of lead-soldered copper pipes and another unit tested the water's corrosivity of clean, standardized lead coupons. Various treatment regimens were evaluated to determine which remedial action(s) successfully lowered copper/lead dissolution to the levels proposed by USEPA.

Scope

This report focuses on a field study done primarily to refine the CERL-PLS for use in lowering copper and lead concentrations. As noted above, details about R&D on the system are in USACERL Technical Report N-88/12. In addition, a draft Technical Note³ contains instructions for fabricating and installing the CERL-PLS.

Mode of Technology Transfer

It is recommended that the CERL-PLS be used Army-wide as the standard apparatus for optimizing water treatment processes where required by regulation. The recommended protocol for determining which water treatment will reduce lead and copper dissolution in plumbing systems will be disseminated to Army installations through a Technical Note. A sample scope of work for contracting a water treatment optimization study will also be distributed to all installations. The U.S. Army Engineering and Housing Support Center (USAEHSC) will be the primary technology transfer agency. An exclusive licensing agreement was negotiated and awarded to transfer production and marketing of the CERL-PLS to the private sector under the provisions of the Technology Transfer Act of 1986. Information in this report also should be used to update Technical Manual (TM) 5-813-3, *Water Supply, Water Treatment*.

³Technical Note 420-46-3, *CERL Pipe Loop System To Evaluate Drinking Water Quality Problems*, (U.S. Army Engineering and Housing Support Center, 1 June 1990).

2 CERL-PLS DESIGN AND FABRICATION

General Features

The development, design, and fabrication of the CERL-PLS have been described in detail in a previous USACERL technical report.⁴ This chapter reviews these features briefly.

Figures 1 and 2 show the CERL-PLS concept and details of the corrosion tester, respectively. The test loop is constructed of 3/4-in.* (nominal) polyvinyl chloride (PVC) and chlorinated polyvinyl chloride (CPVC) pipe and fittings. These materials are readily available and have characteristics suitable for an analytical tool. This design eliminates all metallic components, except for the corrosion test specimens, and electrically isolates the corrosion specimens from each other.

The test loop is oriented vertically to minimize the amount of suspended matter deposited on the exposed surfaces of the corrosion specimens. A flow controller (FC), flow rate meter (FR), and regulating valves (VI) are provided to maintain flow through the loop at desired rates. If fluctuating water pressure occurs, a pressure regulating valve (PRV) can be used on the inlet piping of the test loop. A totalizing water meter (M) is also included in the design to verify water usage information during monitoring intervals.

A static mixer in the loop system is used to mix the water and chemical(s), which can be injected by a chemical metering pump to study the effectiveness of a selected corrosion inhibitor. The continuous flow of both water and inhibitor ensures that constant inhibitor concentrations are in contact with the corrosion specimens at all times. A sampling valve (VI) is installed in the loop to collect water samples periodically for chemical analyses and to verify inhibitor concentrations.

The CERL-PLS design incorporates both pipe inserts and coupon specimens for determining corrosivity of one supply relative to another. The corrosion rate determination is based on weight loss of the pipe insert or metal coupon performed according to American Society for Testing and Materials (ASTM) Standard D 2688-83.⁵ With the CERL-PLS, corrosion tests can be done simultaneously on multiple specimens. Four coupon and four pipe insert specimens can be accommodated by the test loop so that several materials can be studied during the same exposure period, duplicate specimens can be used for statistical evaluation, or the planned interval exposure procedures can be completed. Both coupon and pipe specimens were included so that any differences in corrosion occurring on pipe walls could be compared with the corrosivity of the bulk water.

The USACERL corrosion tester (Figure 2) for placing pipe specimens in the CERL-PLS was developed because the ASTM Standard D 2688-83 Method C corrosion tester 4 could not be incorporated into the test loop due to its size and construction materials. The USACERL design (constructed entirely of PVC) eliminates the sleeve used in the ASTM design, reduces fabrication time and, with its uniform dimensions, allows corrosion testers to be interchanged. Uniform flow with no obstructions is maintained through the tester to simulate deposition or corrosion processes occurring on the walls of piping in distribution systems. Corrosion specimens for this tester can be constructed from any material available in 3/4-in., schedule 40 pipe. Specimens are prepared in accordance with ASTM⁶ procedures. Each pipe specimen exposes 10.25 sq in. of pipe wall to the water.

*T. Prakash et al.

*Metric conversion table is given on p34.

⁵American Society for Testing and Materials (ASTM) Standard D 2688-83, "Standard Test for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Methods)," *ASTM Annual Book of Standards*, Vol 3.02 (1988).

⁶ASTM Standard D 2688-83

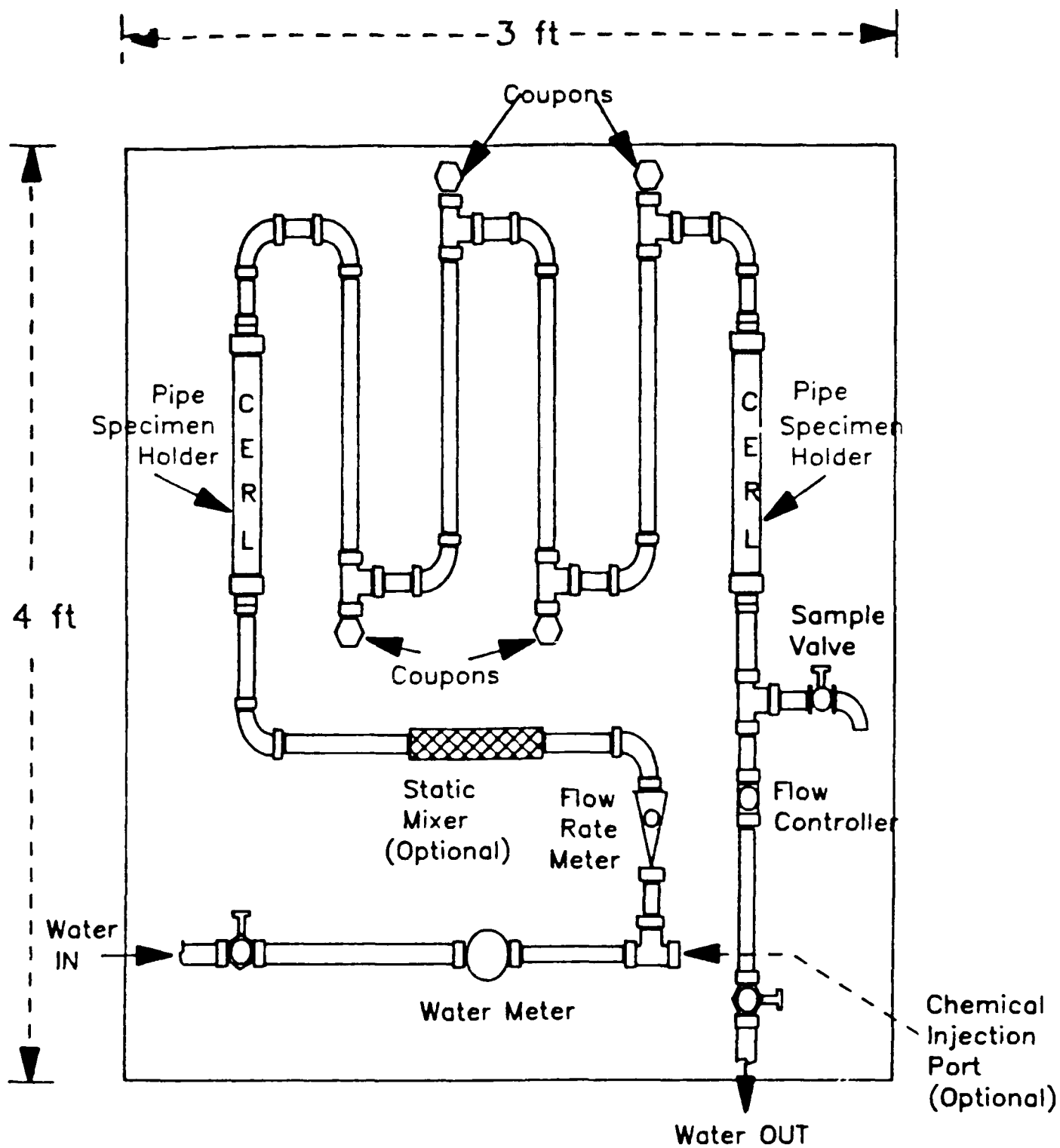
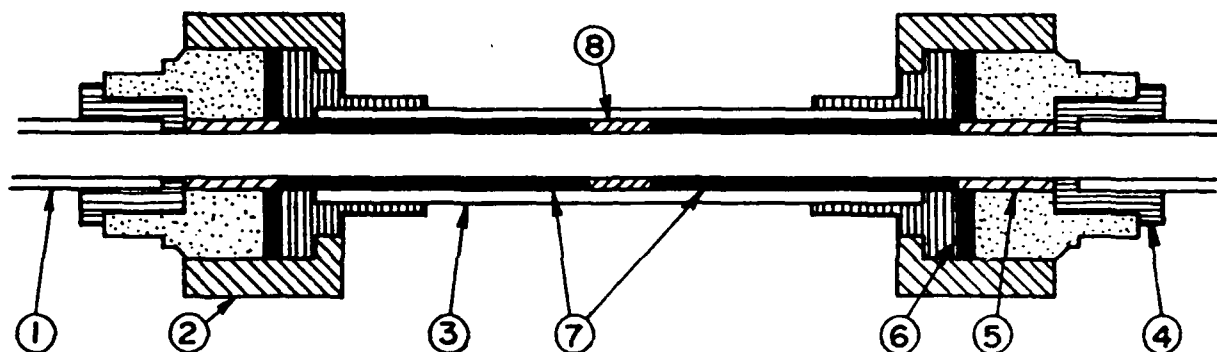


Figure 1. Schematic of the CERL-PLS.



- ① 3/4" PVC SERVICE LINE
- ② 1" UNION, PVC, SOCKET TYPE
- ③ 1 x 10" PIPE NIPPLE, PVC, SCH 40
- ④ 1 x 3/4" REDUCING BUSHING, PVC, SOCKET
- ⑤ 3/4" PVC SPACER, SCH. 40, O.D. REDUCED 0.015"
- ⑥ UNION GASKET
- ⑦ CORROSION SPECIMENS, 3/4", O.D. REDUCED 0.030",
MACHINED FROM SCH. 40 GALVANIZED STEEL OR
STEEL PIPE
- ⑧ 3/4 x \approx 2" SPECIMEN SEPARATOR, PVC, SCH. 40, O.D.
REDUCED 0.015"

Figure 2. Cross section of USACERL corrosion tester.

Four standard metal coupons can be installed in the test loop, all oriented in the same direction in relation to the flow of water through the loop. The 1/2 in. by 3 in. by 1/16 in. coupons are mounted on a PVC pipe plug using a nylon stem (attached to the plug) that protrudes into the middle of the pipe. Each coupon exposes approximately 3.3 sq in. of surface area to the bulk water. The coupons and mounting hardware are commercially available in a variety of materials and can be readily evaluated by most laboratories following ASTM D 2688-83.

All components of the test loop are assembled with the pipe hanger supports on a 3 ft by 4 ft plywood sheet. The completed assembly requires minimal wall space when installed and is easily transported as a complete unit. Figure 3 shows a completely assembled CERL-PLS installed on a wall.

Placing the CERL-PLS in Service

A detailed assembly drawing for in-house fabrication of the pipe loop system is available from USACERL. The coupon specimens and services for determining corrosion rates of exposed coupons are commercially available. The pipe insert specimens need to be specially prepared to meet system specifications.

As mentioned in Chapter 1, an exclusive licensing agreement for commercial production and marketing of the CERL-PLS has been negotiated. In the interim, contact the authors at USACERL for details on procuring a CERL-PLS. The address is USACERL-EN, PO Box 4005, Champaign, IL 61824-4005; telephone (217) 373-6747 (comm), 800-USA-CERL (toll-free outside Illinois), or 800-252-7122 (toll-free inside the state).

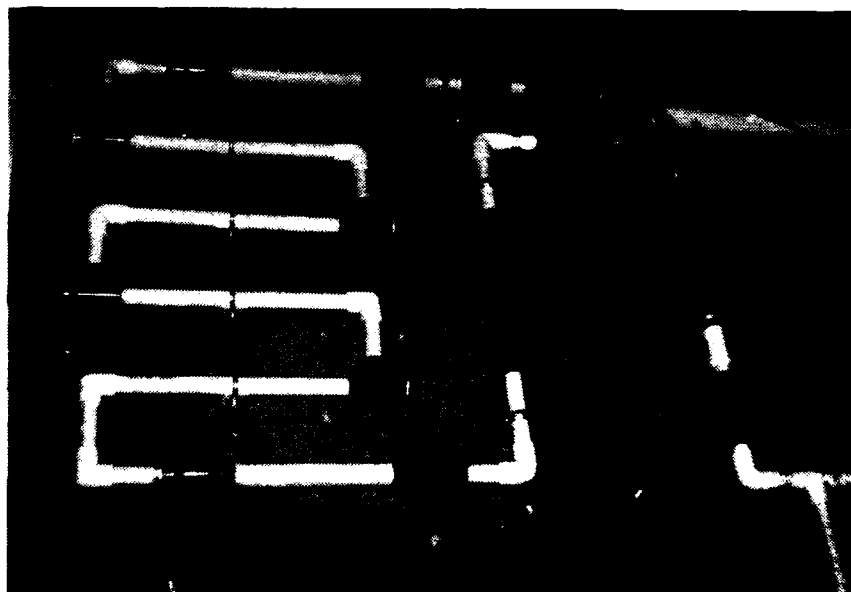


Figure 3. CERL-PLS: completely assembled and installed in a water treatment plant.

3 CERL-PLS INSTALLATION AND OPERATION

The CERL-PLS is designed to be used by water utilities for many purposes, ranging from a simple visual observation of water quality effects on a pipe material to a complete identification of corrosive water impacts on various pipes. The protocol for installing and operating the CERL-PLS varies with the specific reason for doing a corrosion study in the water system. This chapter describes various protocols for CERL-PLS installation and operation to meet specific objectives. These protocols were considered in designing the experiments to be done at Aberdeen Proving Ground.

Criteria for the CERL-PLS Corrosion Test Protocol

The major criteria to consider in developing a protocol for CERL-PLS corrosion tests are:

1. Specimen material selection.
2. Water quality.
3. Simulation of environment.
4. Experimental duration.

Specimen Material Selection

The metal sample must be representative of the metal piping. For monitoring corrosion in an existing system, the specimens used in the CERL-PLS should be prepared from the same material comprising the system being studied. Various materials are used by the water works industry to construct pipes and internal plumbing for the treatment plant, storage areas, and distribution system. Table 1 lists the common materials and their specific uses in a water supply system. Table 2 presents corrosion properties and the associated byproducts of materials used frequently in water distribution systems.

The CERL-PLS uses both pipe inserts and coupons for metal specimens. The inserts are test specimens constructed from a representative length of 3/4-in. pipe of a suitable material. Pipe inserts are prepared according to ASTM D 2688, Method C (Machined-Nipple Test, Illinois State Water Survey) except that they are to be 3.00 in. long and the outside diameter must be reduced so that it will slide easily into the CERL-PLS pipe insert holders.

Coupon specimens used in the CERL-PLS are prepared according to ASTM D 2688, Method B (Coupon Test). Coupon specimens meeting the ASTM specification are commercially available and can be used in the CERL-PLS.

Water Quality

The quality of water passing through the CERL-PLS should be representative of that flowing through the distribution/plumbing system. The water quality within the CERL-PLS can be varied through batch treatment processes or continuous treatment, depending on the objective of the corrosion test. However, the water is not recirculated to avoid changing the corrosion processes due to accumulation of corrosion byproducts.

Table 1
Common Materials Found in Water Supply Systems and Their Uses

Material	In-Pipe Systems		Other Systems			
	Piping	Other	Storage	Transmission and Distribution Mains	Service Lines	Residential and Commercial Buildings
Wrought iron	X	X		X	X	X
Cast/ductile	X	X		X	X	X
Steel	X	X	X	X	X	X
Galvanized iron	X			X	X	X
Stainless Steel		X				X
Copper	X	(Brass)			X	X
Lead		X (Gaskets)		X	X	X
Asbestos-cement	X			X		
Concrete	X	X	X	X		
Plastic	X	X	X	X	X	X

Table 2
Corrosion Properties of Frequently Used Materials in Water Distribution Systems

Distribution Material	Corrosion Resistance	Associated Potential Contaminants
Copper	Good overall corrosion resistance; subject to corrosive attack from high velocities, soft water, chlorine, dissolved oxygen, and low pH	Copper and possible iron, zinc, tin, arsenic, cadmium, and lead from associated pipes and solder
Lead	Corrodes in soft water with low pH	Lead (can be well above MCL* for lead), arsenic, and cadmium
Mild steel	Subject to uniform corrosion; affected primarily by high dissolved oxygen levels	Iron, resulting in turbidity and red-water complaints
Cast or ductile iron (unlined)	Can be subject to surface erosion by aggressive waters	Iron, resulting in turbidity and red-water complaints
Galvanized iron	Subject to galvanic corrosion of zinc by aggressive waters; corrosion is accelerated by contact with copper materials; corrosion is accelerated at higher temperatures as in hot water systems	Zinc and iron; cadmium and lead (impurities in galvanizing process may exceed primary MCLs)
Asbestos-cement	Good corrosion resistance; immune to electrolysis; aggressive waters can leach calcium from cement	Asbestos fibers
Plastic	Resistant to corrosion	

*MCL = Maximum contaminant levels.

In batch treatment operation, a known volume of water can be treated by the desired chemical and then pumped through the CERL-PLS setup. The batch treatment option is helpful in experiments to monitor metal uptake from pipe materials in stagnant waters. Continuous treatment can be provided by injecting chemicals from a reservoir into the CERL-PLS setup while the water is flowing at a constant rate. Figures 4 and 5 show batch and continuous treatment setups, respectively, for the CERL-PLS.

Simulation of Environment

The flow velocity and stagnation times in the CERL-PLS should be representative of those in the full-scale system. To effectively use the CERL-PLS in optimizing water treatment for corrosion control, the system should approximate the flow velocity and stagnation time of the full-scale system. However, protocols can vary widely, depending on the objective of the simulation. Figure 6 is an example flow schedule approximating domestic water consumption; this schedule was used at Portland, OR to determine the corrosivity of a city water to six different piping materials.

Experimental Duration

The specimen exposure should be long enough to allow the corrosion products to affect the metal surface because these reactions influence the corrosion rate and quality of water passing through the system. Therefore, the exposure time and number of exposure periods should be planned carefully before starting a corrosion study. The American Water Works Association (AWWA) has suggested time estimates required to determine the desired information (Table 3).⁷

These times are rough estimates only; specific conditions may make it advisable to use other times. For example, it is often found that initial corrosion rates are considerably higher than those obtained after some time. A planned-interval test allows an evaluation of how time affects both corrosion of the specimen and corrosivity of the environment. The Appendix describes the procedure for doing planned-interval tests as recommended by the National Association of Corrosion Engineers.

Typical CERL-PLS Implementation

Because of the CERL-PLS' segmented, multisample, standardized design, a great variety of experiments is possible. Care must be taken so that data can be compared meaningfully and so that the many complicating factors are controlled as much as possible.

⁷American Water Works Association (AWWA) Research Foundation, *Internal Corrosion of Water Distribution Systems* (1985).

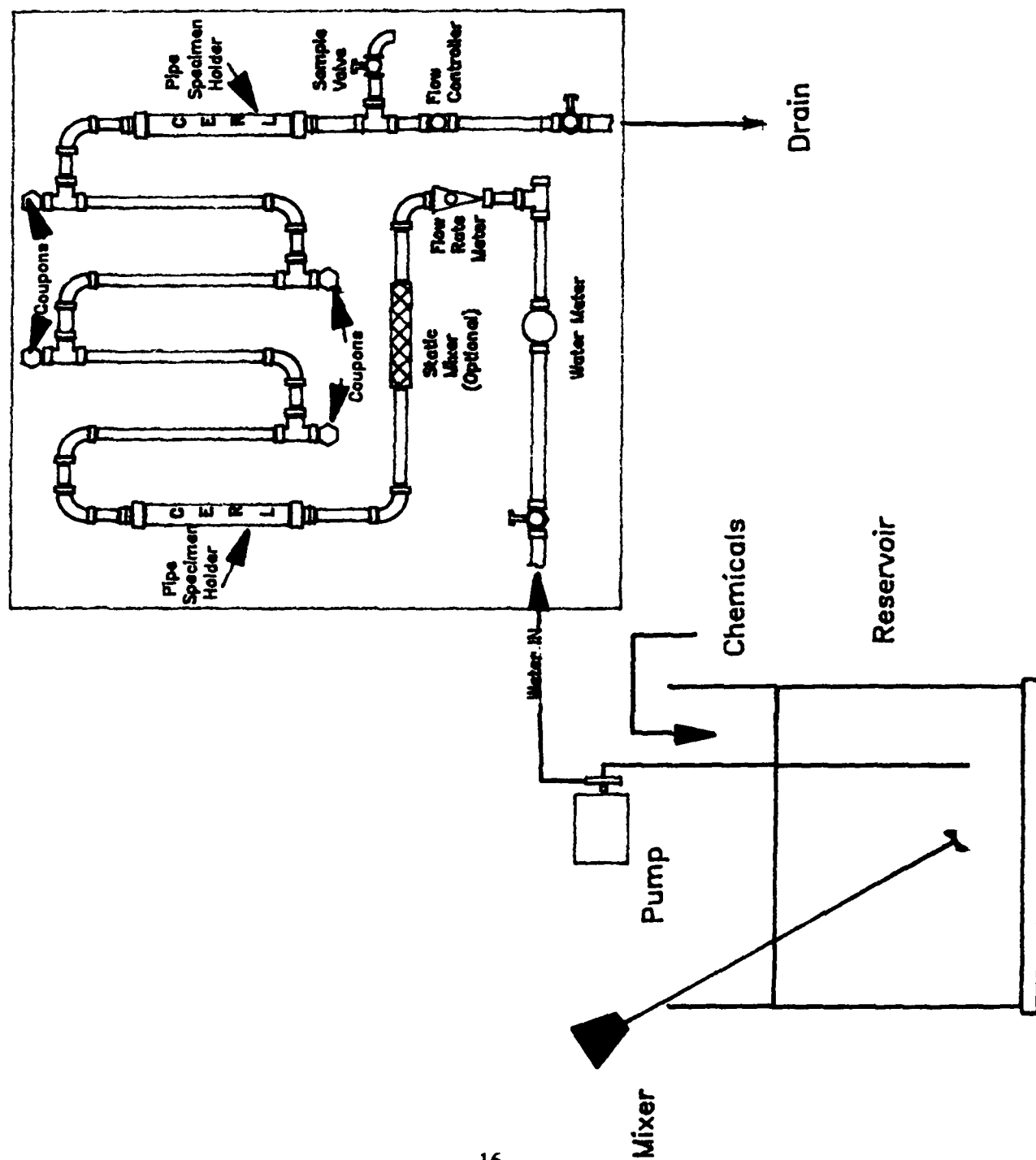


Figure 4. Batch treatment setup for CERL-PLS.

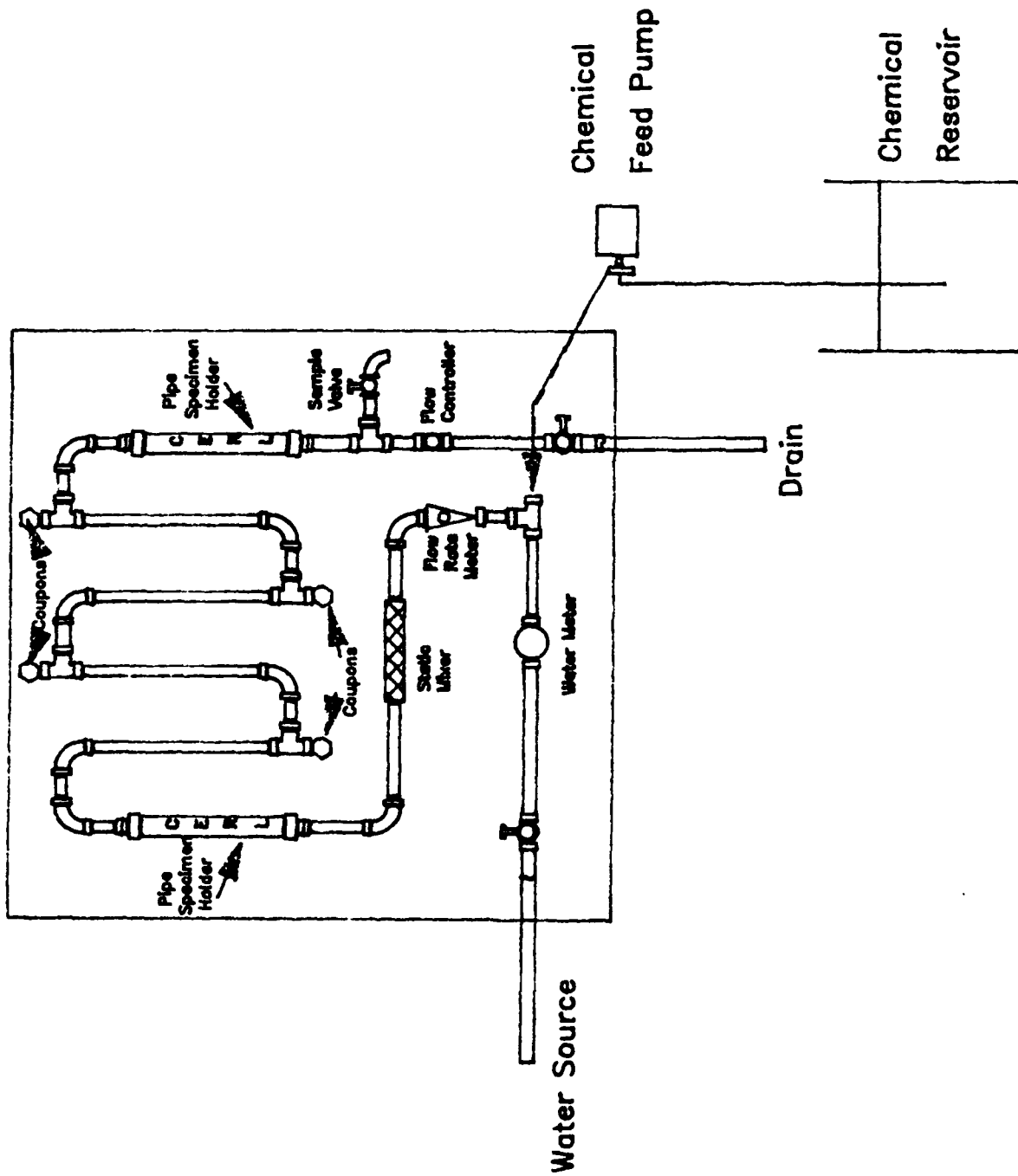


Figure 5. Continuous treatment setup for CERL-PLS.

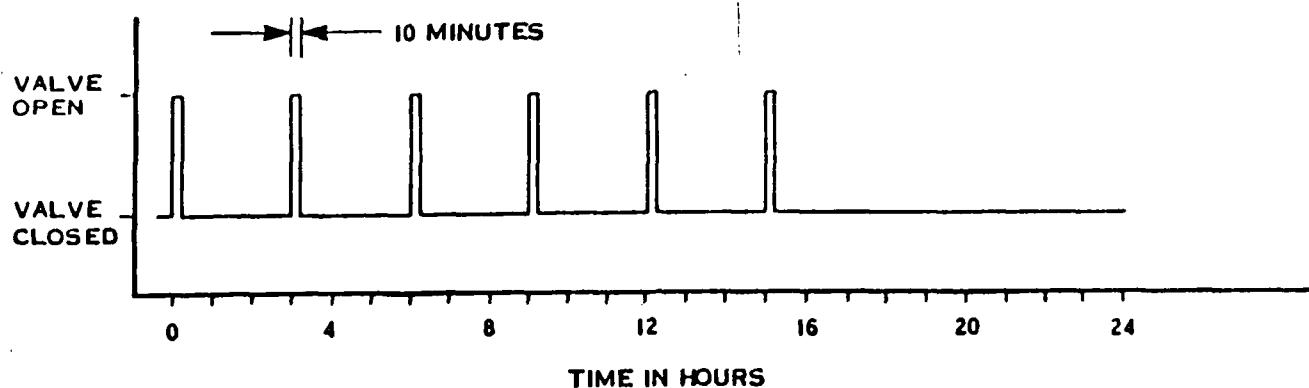


Figure 6. Flow schedule showing on and off periods to simulate domestic use of water.

Table 3

Estimated Duration (Months) Required for Corrosion Tests*

Material	Comparison of Uniform Corrosion Rates or Metal Leaching	Comparison of Inhibitors		Pitting
		New Pipe	Old Pipe	
Iron	12-24	3-6	12-24	12-24
Copper	3-6	1-3	3-6	12-36
Galvanized iron (zinc)	3-6	1-3	6-12	12-36
Lead	6-12	2-6	6-12	
Asbestos cement	18-24	6-12	12-18	
Mortar lining	24-36	12-24	24-36	

* Reprinted from *Internal Corrosion of Water Distribution Systems*, by permission. Copyright ©1985, American Water Works Association.

4 WATER TREATMENT OPTIMIZATION FOR LEAD AND COPPER CONTROL

As noted in Chapter 1, USEPA has issued a proposed rule for limiting lead and copper levels in drinking water. In the proposed rule, water suppliers not meeting the lead and copper limitations will be required to optimize their water treatment process to reduce lead and copper dissolution from plumbing system materials. Further, USEPA recommends use of techniques such as a pipe-loop system to simulate conditions in household plumbing and evaluate various treatment options to reduce lead and copper dissolution.

Several experimental and investigative techniques involving inserts in pipe loops and plumbing systems have been reported for studying internal corrosion in drinking water systems. The Illinois State Water Survey (ISWS) machined nipple test, described in detail in ASTM D 2688, uses a short length of actual pipe material in a PVC pipe sleeve which is connected by pipe unions to the pipe system under test. More complex methods simulating water distribution system conditions have been used to collect specific data.⁸ An experimental apparatus reported in a lead dissolution study by Birden et al.⁹ consisted of 24 sections (20 ft each) of Schedule M copper tubing, 1/2-in. internal diameter (id), connected with 90-degree copper elbows. Various solder materials were evaluated for lead dissolution by drinking water.

Many techniques are reported in the literature for corrosion detection, control, and monitoring. However, until the CERL-PLS was developed, there was a need for a practical, flexible design and protocol to optimize water treatment required to prevent lead and copper dissolution in plumbing systems.

To demonstrate the ability of the CERL-PLS to simulate lead dissolution by a specific quality water and optimize treatment to reduce lead dissolution, the system was evaluated at Aberdeen Proving Ground's Edgewood Water Treatment Plant.

Initial Testing and Remedial Actions

Assessment of Lead in Potable Water Supplies

Lead can enter drinking water from two sources: (1) contaminated raw (source) water and (2) corrosion of plumbing materials in the water distribution system. Most of the lead in drinking water results from the corrosive action of water with plumbing materials that contain lead. The amount of lead in potable water due to corrosion depends on several factors, including the amount and age of lead material present in the system being corroded and the water's degree of corrosivity. Figure 7 shows potential sources of lead in drinking water distribution systems (including plumbing in buildings).

The issue of lead in drinking water supply systems has important health implications. Guidance from Department of Defense (DOD) agencies provides general information on assessment of lead levels in water supply systems and possible remedial strategies for detecting and minimizing lead exposure.¹⁰ Engineer Technical Note (ETN) 87-4 provides information on Federal regulations banning lead-containing materials

⁸R. A. Ryder, "Methods of Evaluating Corrosion," *Proceedings of the 6th Water Quality Technology Conference*, Louisville, KY (AWWA, 1978); G. Treweek, et al., "Modelling Corrosion of Domestic Pipe Materials," *Internal Corrosion of Water Distribution Systems* (AWWA Research Foundation, 1985).

⁹H. H. Birden, Jr., E. J. Calabrese, and A. Stoddard, "Lead Dissolution From Soldered Joints," *Journal of the American Water Works Association*, Vol 77, No. 11 (1985).

¹⁰USAEHA, "Lead in Potable Water Supplies," *Water Quality Information Paper*, No. 43 (16 March 1988).

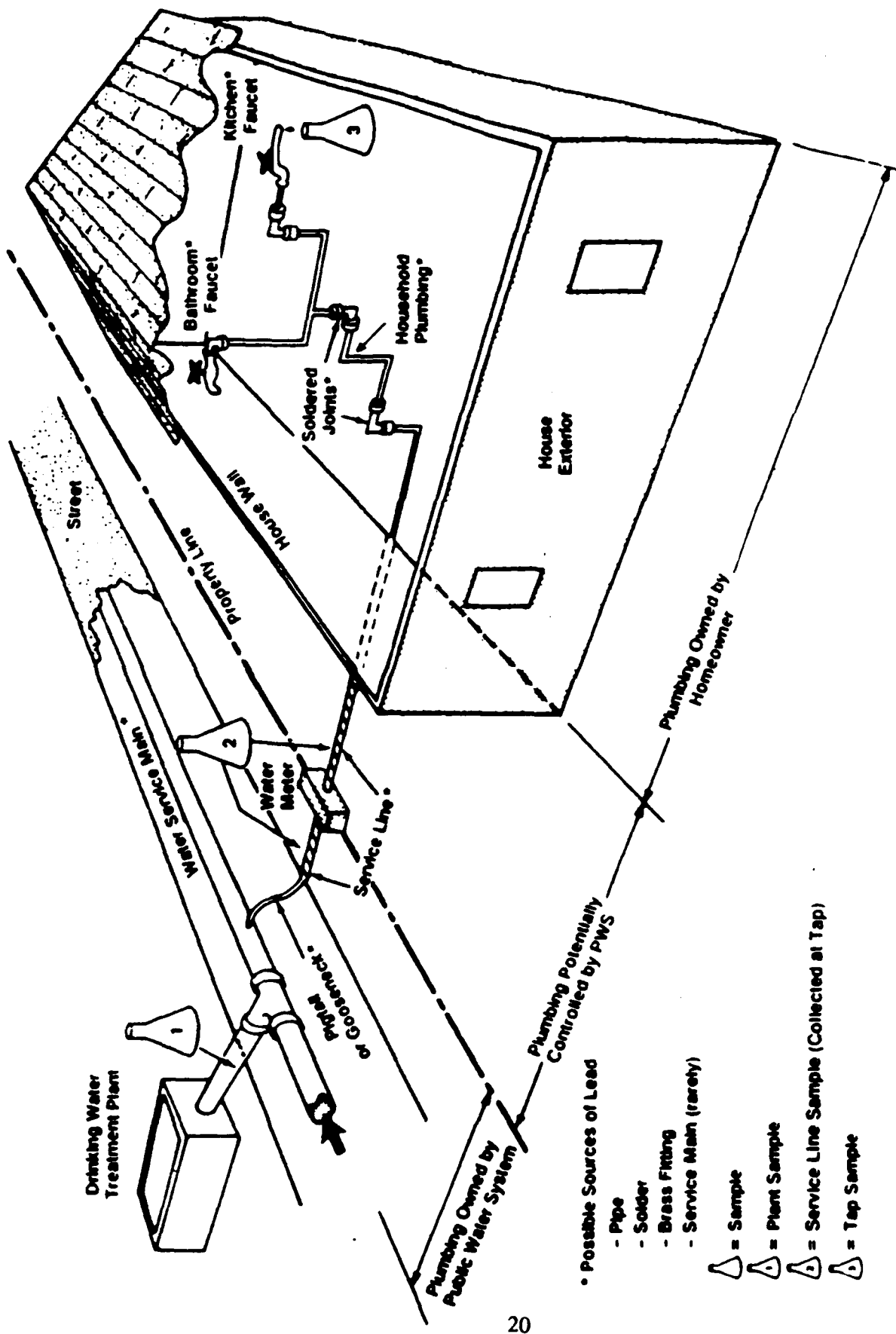


Figure 7. Example public water system and homeowner plumbing showing possible sources of lead.
(Source: *Federal Register*, Vol 50, No. 160 (August 18, 1988), p31516)

in potable water systems and recommends measures for bringing Army installations into compliance with the maximum allowable lead content in drinking water.¹¹ Recommendations from these documents were followed ... developing the experiments at Aberdeen Proving Ground.

Drinking Water Lead Survey

The Edgewood Water Treatment Plant serving part of Aberdeen Proving Ground is located in northeastern United States. The plant has been in service since World War II. In addition to serving the Army installation, this treatment plant also delivers drinking water to a neighboring community. The plant produces water at an average of 2 million gallons per day (mgd). The water source for this installation is a creek with relatively low alkalinity (<5 mg/L) and pH (7.0). The treatment process includes alum coagulation followed by rapid sand filtration, lime treatment for pH adjustment, sodium silicate treatment for corrosion control, fluoridation, and chlorination.

High lead concentrations in the drinking water were discovered at the consumer's tap during a water quality survey initiated due to complaints of discolored water at some points in the distribution system. The survey, conducted by the Water Quality Division of the USAEHA in March 1988, was comprehensive and tested for heavy metals including lead, copper, zinc, and cadmium in the first-flush water samples at the consumer's tap. Except for the lead concentration, all other water quality parameters were within USEPA standards. Table 4 lists the pH and lead concentrations in the overnight stagnant and completely flushed water samples taken at consumer's taps.

As Table 4 shows, the average stagnant and flushed water pH was 7.9. The average lead concentration in stagnant water samples was 0.053 mg/L. More than 43 percent of the samples exceeded the present maximum contaminant level of 0.050 mg lead/L. In addition, about 50 percent of the samples contained more than 0.010 mg lead/L which is the proposed maximum concentration at the consumer's tap. Water samples taken at the plant had less than 0.005 mg lead/L, well within the proposed levels for water entering the distribution system. After complete flushing of the plumbing system, the average lead concentration was 0.001 mg/L. At this time, none of the samples exceeded the proposed lead concentration of 0.010 mg/L at the consumer's tap.

As a result of this survey, several actions were taken to alleviate the high lead levels found in the overnight standing water in the consumer's home. For example, the installation commander issued notification to all grounds personnel to flush water lines in buildings each morning. All family housing units were requested to flush kitchen taps each morning before using the water for drinking and cooking. At the water plant, the lime dosage was adjusted to increase the product water pH to 8.6.

In June 1988, another water quality survey was conducted to determine the status of lead dissolution in plumbing systems. The results of this survey are presented in Table 7. A major change noted in this survey is that the average water pH in the distribution system was 8.5 to 8.6. Only 5 percent of the water samples were reported to have pH less than 8.0. The average lead concentration of stagnant water samples was 0.031 mg/L, which is within the current lead MCL. However, 24 percent of the samples exceeded the 0.050 mg lead/L level. The proportion of water samples exceeding the proposed MCL of 0.010 mg lead/L was still high at 64 percent. After complete flushing, the average lead concentration was 0.001 mg/L--well within the proposed rules.

From these results, it can be concluded that raising the pH to above 8.5 at the water plant did reduce the average lead concentration from the first-draw water samples at the consumer's tap. However, there

¹¹Engineer Technical Note (ETN) 87-4, *Facility Engineer Maintenance and Repair Lead Solder in Potable Water Systems* (Headquarters, USACE, July 87).

Table 4

**Lead Survey Data From Edgewood Water Distribution System:
Before System-Wide Flushing (28 to 31 March 1988)**

Sample Number	pH		Lead (mg/L)		
	Initial	Flushed	Initial	Flushed	
1					
2			0.002	<0.001	
3	7.4	7.5	0.014	0.001	
4	8.5	8.6	0.021	<0.001	
5	8.5	8.4	0.008	<0.001	
6	8.0	7.4	0.086	0.002	
7	7.7	7.4	0.065	<0.001	
8	8.1	7.4	1.200	0.003	
9	8.4	7.4	0.011	<0.001	
10	8.2	7.4	0.006	<0.001	
11	6.7	7.5	0.029	<0.001	
12	7.2	7.4	0.019	<0.001	
13	7.4	7.6	0.002	<0.001	
14	8.1	8.3	0.087	<0.001	
15	7.8	8.3	0.024	0.003	
16	8.5	8.5	0.005	<0.001	
17	9.0	8.9	0.004	<0.001	
18	7.9	8.1	0.006	<0.001	
19	8.0	8.1	0.004	<0.001	
20	8.1	8.2	0.002	<0.001	
21	8.2	8.2	0.009	<0.001	
22	8.1	8.2	0.098	0.003	
23	8.1	8.2	0.018	<0.001	
24	8.1	8.0	<0.001	<0.001	
25	7.8	7.6	0.003	<0.001	
26	8.3	8.4	<0.001	<0.001	
27	7.8	8.1	0.040	0.003	
28					
29					
30	7.0	7.1	0.001	<0.001	
31	7.3	7.4	0.004	0.002	
32	7.1	7.2	<0.001	<0.001	
33	7.3	6.9	0.081	0.002	
34	8.3	8.2	0.020	<0.001	
35	8.4	7.8	0.040	<0.001	
36	7.7	7.8	0.003	<0.001	
37	7.6	7.6	<0.001	<0.001	
38	8.0	8.1	<0.001	<0.001	
39					
40	6.5	6.6	0.077	0.005	
41	8.2	8.2	0.037	<0.001	
42	9.2	9.2	0.005	<0.001	
43					
44					
45					
<hr/>					
Average:		7.9	7.9	0.053	0.001
Lead	% >0.0050			63.2	0.0
Lead	% >0.0100			50.0	0.0
Lead	% >0.0500			43.7	0.0
pH	% <8.0	43.3	51.4		
<hr/>					
pH Range		6.5 - 9.2	6.9 - 9.2		

Table 5

**Lead Survey Data From Edgewood Water Distribution System:
After System-Wide Flushing (6 to 8 June 1988)**

Sample Number	pH		Lead (mg/L)	
	Initial	Flushed	Initial	Flushed
1	8.5	8.5	0.001	0.005
2				
3	8.6	8.6	0.032	0.001
4	8.5	8.6	<0.001	<0.001
5	8.5	8.6		
6	8.8	8.8	0.072	<0.001
7	8.8	8.8	0.018	<0.001
8	8.3	8.8	0.146	<0.001
9	8.8	8.8	0.004	0.007
10	8.4	8.6	0.007	0.001
11	8.8	8.9	0.004	<0.001
12	8.6	8.8	0.024	<0.001
13	8.5	8.6		
14	8.4	8.5	0.095	0.002
15	8.0	8.5	0.025	0.002
16	8.4	8.4		
17				
18	8.3	8.5		
19				
20	8.3	8.4		
21	8.5	8.6		
22	8.5	8.5	0.062	0.002
23	8.6	8.6	0.016	0.002
24				
25				
26	8.7	8.7		
27	8.9	8.9	0.016	0.001
28	8.1	8.5		<0.001
29	8.5	8.4	0.049	<0.001
30	8.3	8.7		
31	8.3	8.7		
32	8.5	8.6		
33	8.6	8.5	0.024	0.001
34	8.7	8.7	0.024	0.001
35	8.2	8.7	0.061	0.005
36	8.6	8.7		
37	8.6	8.7		
38	8.9	8.9		
39	7.8	8.1	0.005	<0.001
40	7.6	8.1	0.028	0.004
41	8.6	8.7	0.007	<0.001
42	9.3	9.1		
43	8.8	8.8	0.008	<0.001
44	8.7	8.7	<0.001	0.001
45	8.2	8.7	0.033	0.001
<hr/>				
Average:	8.5	8.6	0.030	0.001
Lead % >0.0050			76.0	3.8
Lead % >0.0100			64.0	0.0
Lead % >0.0500			24.0	0.0
pH % <8.0	5.0	0.0		
<hr/>				
pH Range	7.6 - 9.3	8.1 - 9.1		

were still many samples (64 percent) that would not be able to meet the proposed limits of 0.010 mg lead/L. Hence, the remedial action of increasing the water pH to above 8.5 was not sufficient to meet the proposed lead standards. Also, it was later noted that the water plant was treating the water for corrosion control by adding sodium silicate at a dosage of 0.5 mg/L. The significance of this treatment on reducing lead dissolution from plumbing materials could not be evaluated.

Experiments To Optimize Treatment for Reducing Lead

Experimental Design

In August 1988, experiments using the CERL-PLS were conducted at the water treatment plant to determine optimal water treatment for reducing lead dissolution from the plumbing system, which is joined with lead solders. Two CERL-PLS units were installed at the water plant in series as shown in Figure 8.

Loop A was fitted with a copper loop having a 50/50 ratio of lead and tin soldered joints. The copper loop was about 6 ft long and contained 22 joints. This loop was built by a licensed plumber following standard plumbing practice. In addition to the copper loop, two galvanized pipe sections were inserted into the CERL-PLS, one on each side of the copper loop.

The second CERL-PLS, loop B, was provided with four lead coupons (1/2 in. wide by 3 in. long by 1/8 in. thick). The coupons were certified to be pure lead. Before insertion, they were polished thoroughly with emery cloth to remove any coatings on the surface. In addition to the four coupons, four pipe sections--two each of copper and galvanized iron--were installed to determine the dissolution potential of copper and zinc.

Altogether, four experiments were conducted. The water samples were collected during each experiment following a predetermined protocol. Loop A remained the same throughout the four experiments, whereas in Loop B, the four coupons were replaced with clean, polished coupons at the beginning of each experiment. The sampling protocol and collection schedule are shown in Figure 9.

The experiment was designed to simulate water usage patterns in a typical household and also to determine the effect of stagnation time on lead dissolution. Experiments were started each morning at 8 a.m. by flushing the loop system for 1 hr at a rate of 2 gallons per minute (gpm). Just before 9 a.m., a water sample was collected from both loops while water was flowing through the system. This sample, no. 1, represented the water entering the distribution system. At 9 a.m., the water flow was stopped by closing the ball valves at both ends each of loops A and B. After a stagnation period of 1 hr (10 a.m.), water samples were collected from loops A and B. This sampling was done by first slowly opening entrance valve for loop A, collecting a sample from the sample port, then opening the exit valve for loop A and entrance valve for loop B, and finally collecting a water sample from the sample port for loop B. This sample, no. 2, represented water after a 1-hr stagnation period in the system. After sample collection, the water was flushed through the system for another hour (10 a.m. to 11 a.m.) at 2 gpm. Again, the water was shut off and allowed to stagnate for 5 hr (11 a.m. to 4 p.m.). The 5-hr stagnated samples, no. 3, were collected using the same procedure for the 1-hr samples described above. The system was flushed for another hour (4 p.m. to 5 p.m.) at 2 gpm. A final sample (no. 4) taken at 8 a.m. the following morning represented the 15-hr stagnated water in the system.

A total of 750 mL was collected for each sample and was then split into two portions of 500 and 250 mL. The 250-mL portion was acidified to pH <2.0 using 1:1 nitric acid and was used for metal analysis. The 500-mL sample was refrigerated and later evaluated for alkalinity (total and carbonate) and total dissolved solids. The samples were sent to USAEHA laboratories, where they were analyzed following standard procedures.

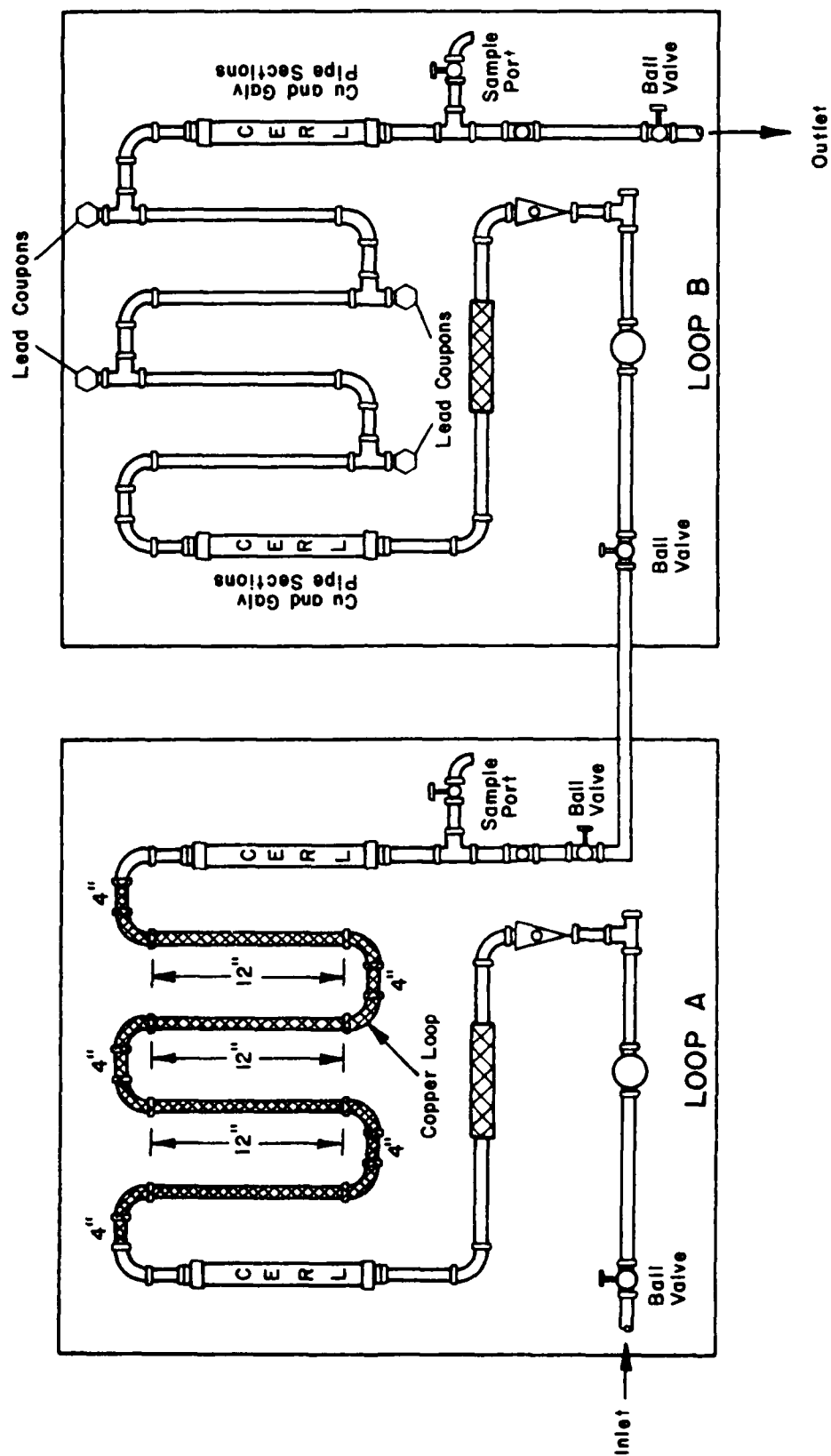


Figure 8. Experimental setup for lead dissolution study.

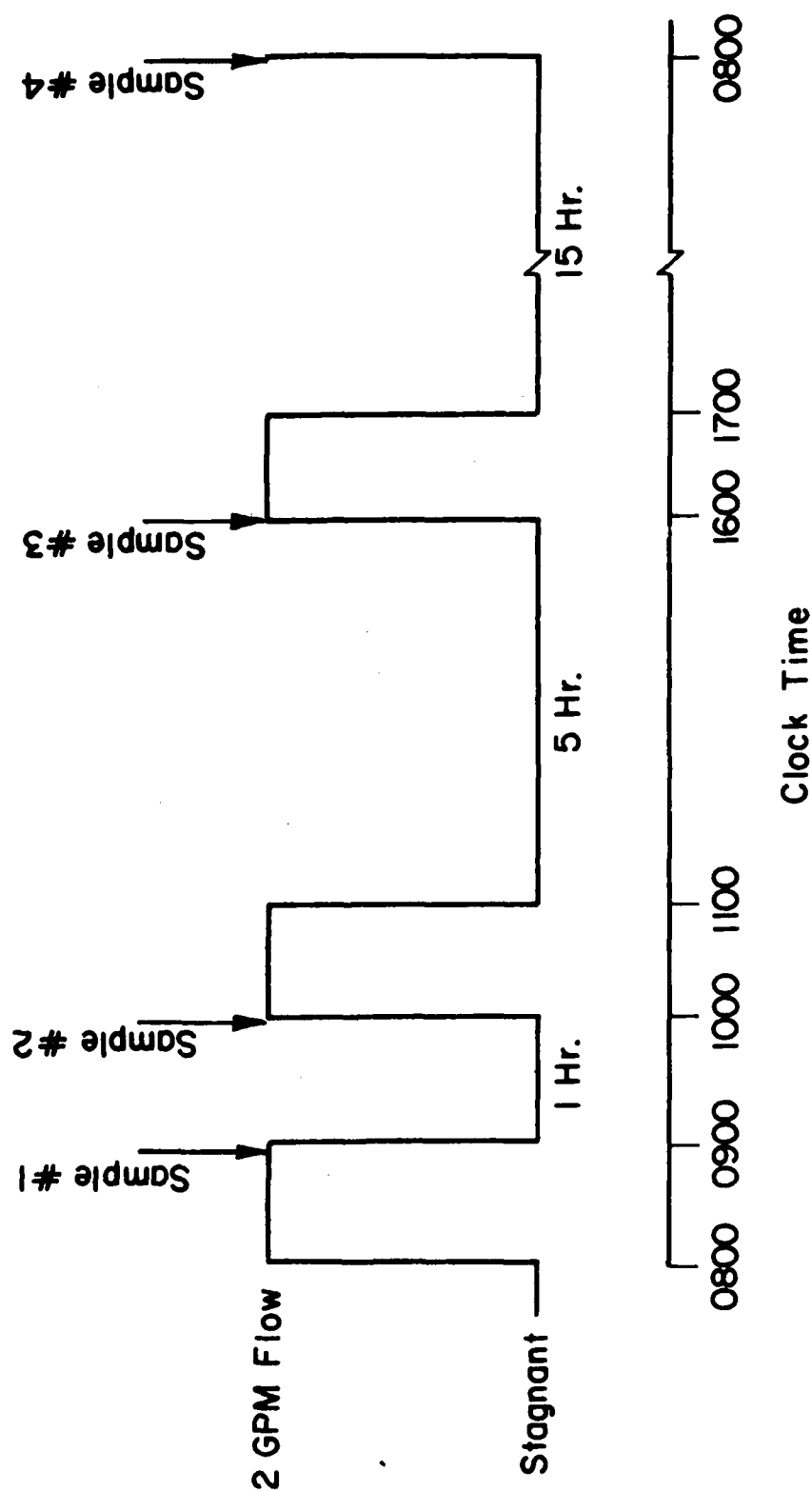


Figure 9. CERL-PLS lead dissolution study: sampling protocol and collection schedule.

The four experimental conditions in this study were as follows:

- Experiment no. 1: water as produced at the plant without further treatment--control water. Table 6 presents typical water quality.
- Experiment no. 2: control water + sodium bicarbonate to raise the total alkalinity to 150 mg/L as CaCO_3 .
- Experiment no. 3: control water + sodium silicate to raise the sodium silicate concentration to 10 mg/L.
- Experiment no. 4: control water + sodium bicarbonate to raise the total alkalinity to 150 mg/L + sodium silicate to raise the sodium silicate concentration to 10 mg/L.

Except for experiment no. 1, water was treated by batch process using 30-gal plastic reservoirs and then pumped through the system. For experiment no. 1, the distribution system water was connected directly to the experimental system.

Table 6
Typical Water Quality Data From Edgewood Water Treatment Plant

Parameter	Measured Value
pH	8.8
Temperature	28 °C
Alkalinity (total)	35 mg/L CaCO_3
Hardness (total)	82 mg/L CaCO_3
Iron (total)	<0.1 mg/L
Copper (total)	<0.1 mg/L
Calcium	20 mg/L
Lead	<0.001 mg/L
Copper	<0.025 mg/L
Zinc	<0.015 mg/L
Cadmium	<0.001 mg/L

Interpreting the Results

Table 7 lists the lead concentrations in water samples collected during this study. As the table shows, the average lead concentration of water entering the distribution system was 0.005 mg/L, with a range of 0.002 to 0.009 mg/L. The lead concentration increased with increasing stagnation time in all experiments. This trend is graphed in Figures 10 and 11 for loops A and B, respectively. These figures suggest that significant differences occurred in lead dissolution for each treatment condition. However, there are major variations between loop A and loop B data; these variations had to be considered when interpreting the data.

The results of loop A experiments (Figure 10) show that the lead concentration declined with each experiment, regardless of the treatment. Lead dissolution from the soldered joints of the copper loop in these experiments depends on two major factors. The primary factor is the total lead available for dissolution by water. In loop A experiments, since the copper loops were not replaced at the beginning of each experiment, the total lead available was greatly reduced at the end of each experiment, although the same surface area was exposed. The secondary factor is the effect of treatment on the water's lead dissolution characteristics. Although the data available do not differentiate between the two factors, the fraction of lead dissolved due to water treatment alone was probably negligible compared with the fraction dissolved by the control water. To determine the effect of water treatment alone on lead dissolution from soldered joints, a new, identical copper loop could be used for each experiment. However, before the water treatment's effect could be evaluated, longer experimental periods would be required for reducing the lead levels to simulate distribution system conditions. Also, fabrication of copper loops with identical solder exposure surfaces would be difficult and result in experimental uncertainties.

Table 7
CERL-PLS Lead Dissolution Study: Lead Concentrations
(mg Lead/L)

Loop / Expt. #	Stagnation Time (Hr)				Experimental Conditions
	0	1	5	15	
A / 1	0.0096	0.3010	0.8850	1.1580	Finished water from WTP
A / 2	0.0044	0.0806	0.2160	0.3870	Treated w/ NaHCO ₃
A / 3	0.0011	0.0411	0.1400	0.1620	Treated w/ Na silicate
A / 4	0.0071	0.0153	0.0402	0.0597	Treated w/ NaHCO ₃ + Na silicate
B / 1	0.0068	0.0172	0.0522	0.0829	Finished water from WTP
B / 2	0.0029	0.0178	0.0358	0.0699	Treated w/ NaHCO ₃
B / 3	0.0046	0.0112	0.0307	0.0471	Treated w/ Na silicate
B / 4	0.0072	0.0193	0.0429	0.0569	Treated w/ NaHCO ₃ + Na silicate

* Average lead concentration in finished water used in the experiments = 0.005 mg/L.
Standard deviation of lead concentration in finished water used in the experiments = 0.002.

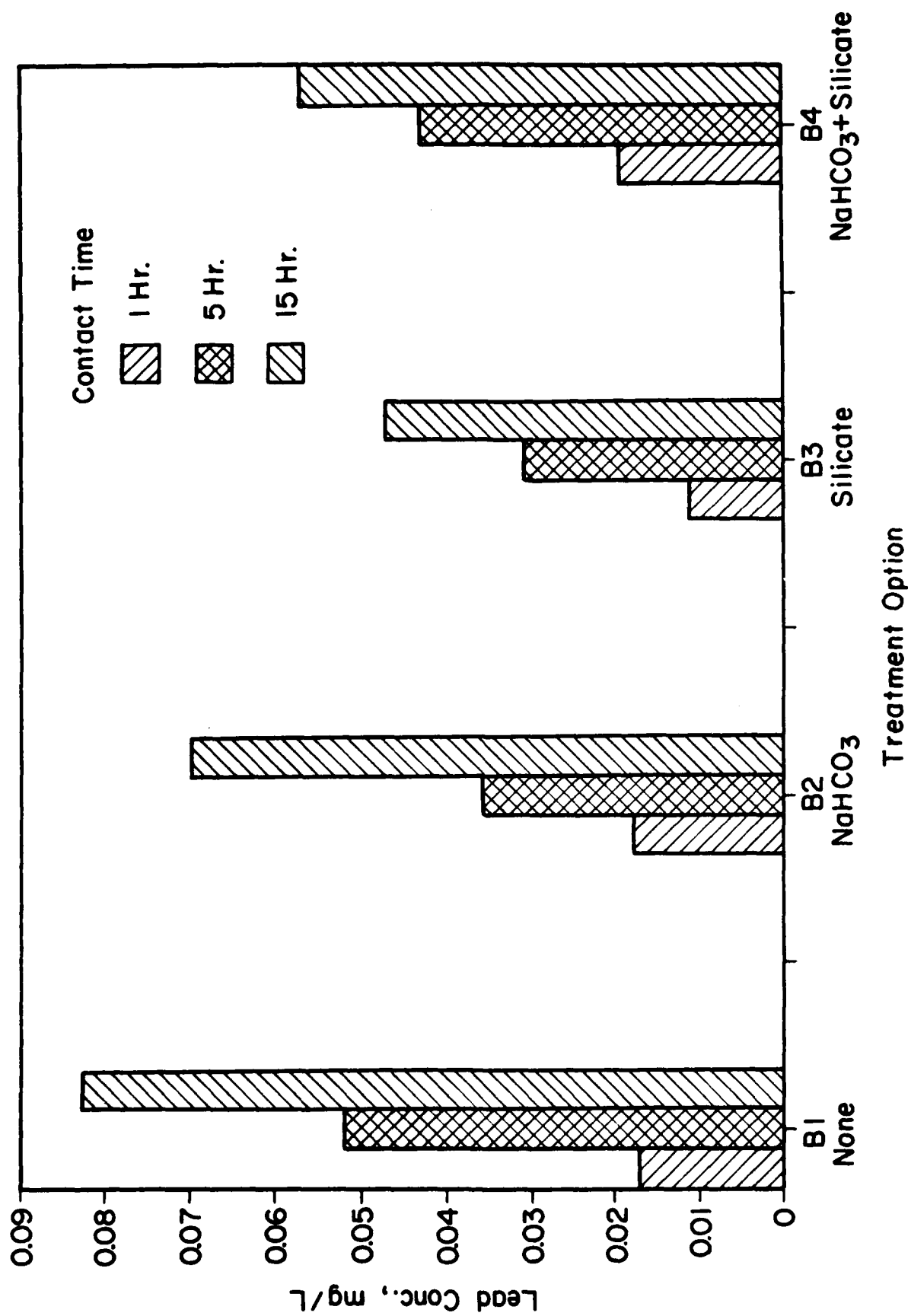


Figure 10. Lead leaching from copper loop with soldered joints in CERL-PLS: loop A.

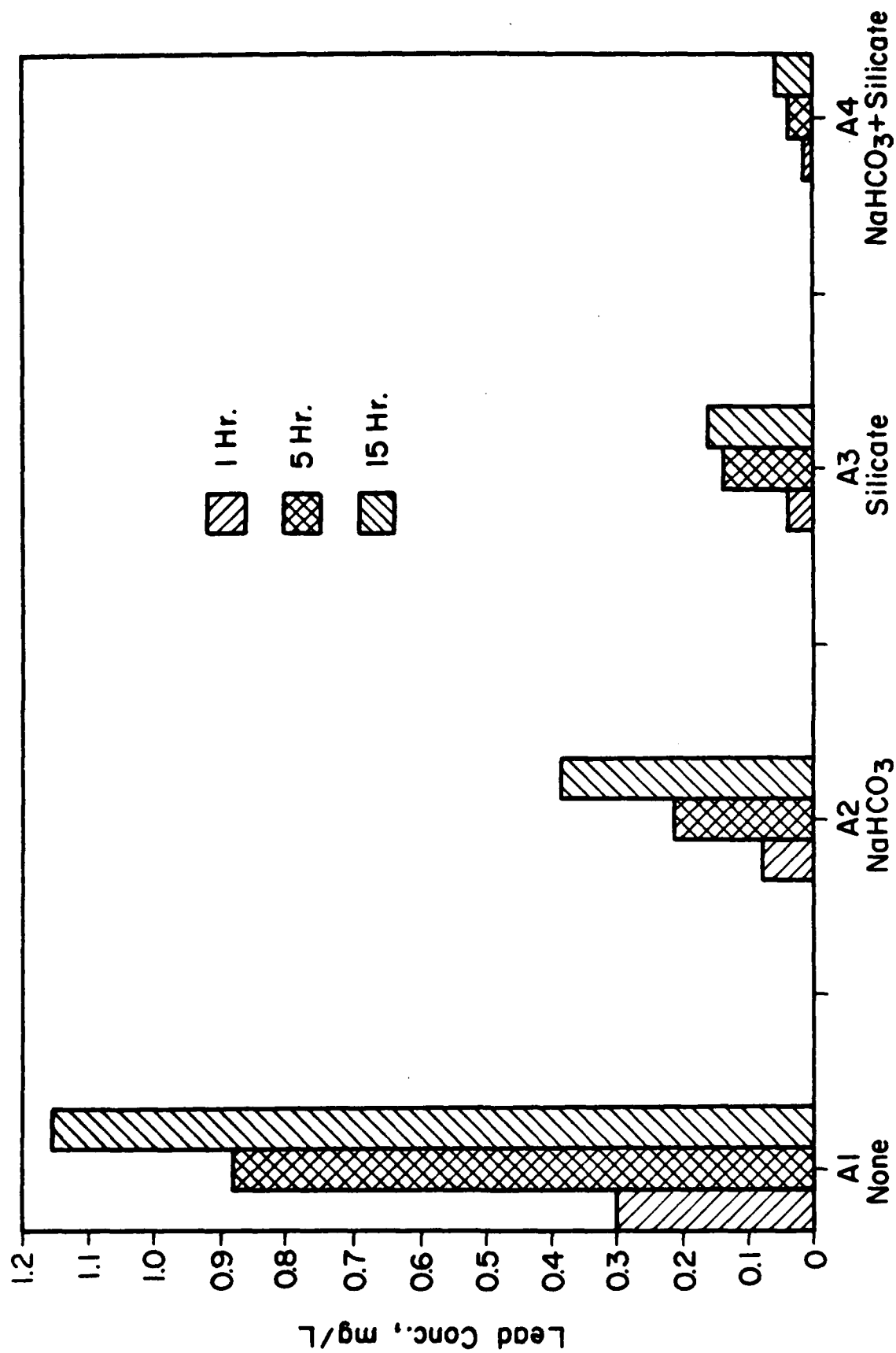


Figure 11. Lead leaching from lead coupons in CERL-PLS: loop B.

The experimental conditions for loop B were better controlled compared with loop A, and offer more insight into the water treatment's effect on lead dissolution characteristics. Four lead coupons with a total exposure area of approximately 13.5 sq in. were installed in the CERL-PLS and represented the only source for lead dissolution. Coupons with clean, polished surfaces were used at the beginning of each experiment. Hence, the loop B data (Figure 11) show the effect of water treatment alone on the lead dissolution characteristics. As seen in the figure, the sodium silicate treatment without increased alkalinity was the most effective treatment among the options tested. However, lead concentrations in the 15-hr stagnated water samples for all treatment options were higher than the proposed limit of 0.010 mg lead/L. Nevertheless, these data demonstrate the relative effectiveness of the different water treatment options and could be used for preliminary evaluation. The long-term effects of an optimized treatment option could then be studied. (However, the protocol for long-term monitoring is not yet established.)

Experiments on the Simulation Protocol

One of the important functions of a pipe-loop system is to be able to simulate a water's lead dissolution characteristics as would be observed in a plumbing system. Since the physical condition of plumbing systems among various households served by a water distribution system varies widely, it is difficult to establish simulation standards for a pipe-loop system. However, lead survey data obtained from a distribution system, as was done at Aberdeen Proving Ground, can be used to establish the simulation conditions. The following example shows how lead survey data and the CERL-PLS experimental results can be used to determine the pipe-loop system simulation conditions.

The June 1988 water quality survey data (Table 5) show that the lead concentrations in stagnant water range from <0.001 mg/L to 0.146 mg/L. This variation could be due to many factors, including differences in plumbing materials, total amount of water passed through the system, water use pattern, and location in the distribution system. The target lead concentration to be simulated in a pipe-loop system can be selected based on several criteria, such as:

1. Average lead concentration observed in the survey.
2. Average lead concentration of samples above analytical detection limit (0.001 mg/L).
3. Average lead concentration of samples above the proposed USEPA limits (0.010 mg/L).
4. Maximum lead concentration observed in the survey.

Based on these criteria, the target lead concentrations for simulating the Edgewood Water Treatment Plant conditions are shown in Table 8. By comparing these data with results of the loop A experiments, it is observed that initial lead levels for control water (expt. no. 1, 15-hr stagnated water) are very high (1.158 mg/L). Since the observed lead concentration is directly proportional to the lead solder surface area exposed to the water, reducing the number of joints in the copper loop could perhaps reduce the lead concentration. However, it would be very difficult to control the exposed lead solder surface area among identical copper loops because of the variation in individual plumbing practices. Hence, using copper loop with lead-soldered joints to simulate distribution system conditions would be difficult, if not impossible. However, the copper loop could conceivably be used for simulating a new plumbing system to determine the cumulative reduction in lead dissolution from solder joints over long periods of water flow through the system. Also, the copper loop could be used to evaluate different solder materials.

Table 8**Lead Dissolution Simulation Criteria Based on June 1988 Lead Survey**

Criterion	Lead Concentration (mg/L)
Average lead concentration of all samples	0.032
Average lead concentration of samples exceeding detection limit of 0.001 mg/L	0.033
Average lead concentration of samples exceeding proposed EPA lead limits of 0.010 mg/L	0.045
Maximum lead concentration observed in the survey	0.146

Results of the loop B experiments show that the observed lead concentration of 0.083 mg/L (15-hr sample from control water experiment expt. no. 1) agrees well with the simulation criterion range presented in Table 8. The lead exposure surface area in the loop B configuration could possibly be modified--by varying the size and number of coupons--to conform with the lead dissolution characteristic of any particular criterion. Further, the coupon material could be changed to represent the solder material used in the plumbing system. It appears that a pipe-loop system in the loop B configuration is better at simulating lead dissolution characteristics of a water compared with the loop A configuration. However, additional data are required before a standard simulation protocol can be developed.

In addition to lead concentration in the CERL-PLS experiments, other heavy metals including zinc, copper, and cadmium were measured. The sources of these heavy metals were the copper and galvanized pipe sections installed in the CERL-PLS. Complete data for the four experiments are presented in Table 9. The table shows that, although measurable quantities of zinc and copper were leached into the water during the experiments, none of these metals exceeded the USEPA maximum contaminant levels. The data further indicate that the CERL-PLS can simulate, in general, the corrosivity of a water to representative materials of a plumbing system.

Table 9

**CERL-PLS Lead Dissolution Study: Heavy Metal Concentrations
(mg/L)***

Loop / Expt #	Stag. Time (hr)	pH	Pb	Cu	Zn	Cd
A / 1	0	8.8	0.0096	0.000	0.000	0.000
A / 1	1	9.2	0.3010	0.000	0.124	0.000
A / 1	5	8.2	0.8850	0.077	0.342	0.001
A / 1	15	8.8	1.1580	0.059	0.478	0.000
A / 2	0	8.6	0.0044	0.000	0.000	0.000
A / 2	1	8.5	0.0806	0.056	0.067	0.000
A / 2	5	8.4	0.2160	0.167	0.267	0.000
A / 2	15	8.4	0.3870	0.289	0.600	0.001
A / 3	0	9.1	0.0011	0.000	0.000	0.000
A / 3	1	8.6	0.0411	0.000	0.094	0.001
A / 3	5	8.5	0.1400	0.064	0.315	0.000
A / 3	15	8.5	0.1620	0.061	0.944	0.000
A / 4	0	8.1	0.0071	0.000	0.000	0.000
A / 4	1	8.2	0.0153	0.080	0.103	0.000
A / 4	5	8.4	0.0402	0.186	0.340	0.000
A / 4	15	8.3	0.0597	0.271	0.702	0.000
B / 1	0	8.7	0.0068	0.000	0.000	0.001
B / 1	1	9.2	0.0172	0.000	0.080	0.001
B / 1	5	8.4	0.0522	0.053	0.180	0.001
B / 1	15	9.1	0.0829	0.041	0.673	0.001
B / 2	0	8.6	0.0029	0.057	0.000	0.000
B / 2	1	8.5	0.0178	0.032	0.049	0.000
B / 2	5	8.4	0.0358	0.080	0.185	0.000
B / 2	15	8.5	0.0699	0.128	0.370	0.000
B / 3	0	9.1	0.0046	0.000	0.000	0.000
B / 3	1	9.0	0.0112	0.000	0.071	0.000
B / 3	5	8.6	0.0307	0.032	0.315	0.000
B / 3	15	8.6	0.0471	0.028	0.787	0.000
B / 4	0	8.2	0.0072	0.000	0.000	0.000
B / 4	1	8.3	0.0193	0.066	0.044	0.000
B / 4	5	8.4	0.0429	0.038	0.164	0.000
B / 4	15	8.3	0.0569	0.059	0.143	0.000

* A value of zero indicates concentration less than the detection limit.

Detection limits, (mg/L) are as follows: Pb = 0.001; Cu = 0.025; Zn = 0.015; Cd = 0.001.

5 CONCLUSIONS AND RECOMMENDATIONS

USACERL has developed the CERL-PLS to objectively evaluate the effectiveness of water quality control chemicals in protecting the water infrastructure. The system is designed so that samples of distribution system materials can be placed in direct contact with water under conditions simulating typical operation. In this way, the water's corrosivity to various materials comprising the system can be assessed and treatment protocols developed and tested to determine optimal conditions.

For maximum effectiveness, the CERL-PLS needs to simulate as closely as possible conditions in the water distribution system under test. To assess the current method of estimating these conditions, as well as to test the system's ability to optimize water treatment for lowering lead and copper levels, a field demonstration was conducted at the Edgewood Water Treatment Plant, which supplies Aberdeen Proving Ground.

Two experiments were conducted using the CERL-PLS to simulate lead dissolution from (1) lead-soldered loop inserts and (2) lead coupons in a drinking water distribution system. The experiments included treatment with sodium bicarbonate and sodium silicate to determine if the increased alkalinity or silicate would reduce lead dissolution. The experimental results were compared with data on the lead concentrations taken in an earlier survey of the same distribution system. It appears that the CERL-PLS can successfully approximate the conditions necessary to select a treatment method to reduce lead dissolution.

The experimental data showed that it is feasible to approximate lead dissolution in soldered plumbing systems using the CERL-PLS with lead coupons. The effect of various treatment options can then be evaluated. However, further study and extensive data are needed before a standardized simulation protocol can be established.

Despite the need for further research to improve simulation accuracy, the performance of the CERL-PLS has been verified in the field numerous times and can be very useful in its current form. It provides a simple, inexpensive, and reproducible method with few manpower requirements (for collecting and analyzing water samples, preparing experimental chemicals, etc.). It is recommended that water utilities regulated by strict water quality standards install one or more CERL-PLS units on their distribution systems to optimize water treatment practices. If the USEPA proposed limits on copper and lead are enacted, this study has shown that the CERL-PLS will also be effective in determining remedial actions for compliance.

METRIC CONVERSION TABLE

1 in.	=	2.54 cm
1 ft	=	0.385 m
1 sq ft	=	0.092 m ²
1 lb	=	0.453 kg
1 gal	=	3.785 L
°F	=	(°C x 1.8) + 32

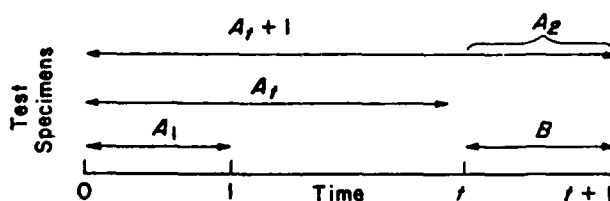
APPENDIX

PLANNED INTERVAL TESTS*

These tests involve not only the accumulated effects of corrosion at several times under a given set of conditions but also the initial rate of corrosion of fresh metal, the more or less instantaneous corrosion rate of metal after long exposure, and the initial corrosion rate of fresh metal during the same period of time as the latter. The rates, or damage in unit time interval, are referred to in the diagram of Table A1a-c as A_1 , A_2 , and B , respectively. Unit time interval may often be taken conveniently as 1 day in a planned-interval test extended over a total period of several days. It would be desirable to have duplicate specimens for each interval, and further time extensions of test could be made with similar added specimens and interval spacing.

Comparison for corrosion damage A_1 for the unit time interval from 0 to 1 with corrosion damage B for the unit time interval from t to $t + 1$ shows the magnitude and direction of change in corrosiveness of the medium that may have occurred during the total time of the test. Comparison of A_2 with B , where A_2 is the corrosion damage calculated by subtracting A_1 from $A_t + 1$, correspondingly shows the magnitude and direction of change in corrodibility of the metal specimen during the test. These comparisons may be taken as criteria for the changes and are tabulated in Table A1. Also given in Table A1 are the criteria for all possible combinations of changes in corrosiveness of the medium and corrodibility of the metal. Additional information thus obtained on occurrences in the course of the test justifies the extra effort involved. An example of the data obtained from a planned-interval test is given in Table A2.

Table A1a
Planned-Interval Test



Identical specimens placed in same corrosive fluid; imposed conditions of test constant for entire time ($t + 1$); A_1 , A_t , $A_t + 1$, B , represent corrosion damage experienced by each test specimen; A_2 is calculated by subtracting A_1 from $A_t + 1$.

*M. Fontana and N. Greene, *Corrosion Engineering*, 2nd Ed (McGraw-Hill, Inc., 1967), pp 125-127. Used with permission.

Table A1b
Occurrences During Corrosion Test

Liquid Corrosiveness	Criteria	Metal Corrodibility	Criteria
Unchanged	$A_1 = B$	Unchanged	$A_2 = B$
Decreased	$B < A_1$	Decreased	$A_2 < B$
Increased	$A_1 < B$	Increased	$B < A_2$

Table A1c
Combinations of Situations

Liquid Corrosiveness	Metal Corrodibility	Criteria
1. Unchanged	Unchanged	$A_1 = A_2 = B$
2. Unchanged	Decreased	$A_2 < A_1 = B$
3. Unchanged	Increased	$A_1 = B < A_2$
4. Decreased	Unchanged	$A_2 = B < A_1$
5. Decreased	Decreased	$A_2 < B < A_1$
6. Decreased	Increased	$A_1 > B < A_2$
7. Increased	Unchanged	$A_1 < A_2 = B$
8. Increased	Decreased	$A_1 < B > A_2$
9. Increased	Increased	$A_1 < B < A_2$

Table A2
Planned-Interval Corrosion Test*

	Interval, days	Weight loss, mg	Penetration, mils	Apparent corrosion rate, mpy
A_1	0-1	1080	1.69	620
A_1	0-3	1430	2.24	270
$A_1 + 1$	0-4	1460	2.29	210
B	3-4	70	0.11	40
A_2	calc. 3-4	30	0.05	18
$A_2 < B < A_1$ $0.05 < 0.11 < 1.69$				

*Conditions: Duplicate strips of low-carbon steel, 3/4 x 3 in., immersed in 200 ml of 10% AlCl₃-90% SbCl₃ mixture through which dried HCl gas was slowly bubbled at atm pressure, 90°C. Liquid markedly decreased in corrosiveness during test, and formation of partially protective scale on the steel was indicated.

Causes for the changes in corrosion rate as a function of time are not given by the planned-interval test criteria. Corrosiveness of the liquid may decrease as a result of corrosion during the course of a test owing to reduction in concentration of the corrosive agent, to depletion of a corrosive contaminant, to formation of inhibiting products, or to other metal-catalyzed changes in the liquid. Corrosiveness of the liquid may increase owing to formation of auto-catalytic products or to destruction of corrosion inhibiting substances, or to other catalyzed changes in the liquid. Changes in corrosiveness of the medium may arise also from changes in composition that would occur under the test conditions even in the absence of metal. To determine if the latter effect occurs, an identical test is run without test strips for the total time t ; then test strips are added and the test continued for unit time interval. Comparison with A_t of corrosion damage from this test will show if the corrosive character of the liquid changes significantly in the absence of metal.

Corrodibility of the metal in a test may decrease as a function of time owing to formation of protective scale, or to removal of the less resistant surface layer of metal. Metal corrodibility may increase owing to formation of corrosion-accelerating scale or to removal of the more resistant surface layer of metal. Indications of the causes of changes in corrosion rate often may be obtained from close observation of tests and corroded specimens and from special supplementary tests designed to reveal effects that may be involved.

Changes in solution corrodibility are not a factor in most plant tests that consist of once-through runs or where large ratios of solution volume to specimen area are involved.

If the effect of corrosion on the mechanical properties of the metal or alloy is under consideration, a set of unexposed specimens is needed for comparison.

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